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U. S. NAVAL UNDERWATER ORDNANCE STATION
NEWPORT, RHODE ISLAND

ELECTROMAGNETIC RADIATION IN SEA WATER

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U. S. NAVAL UNDERWATER ORDNANCE STATION
NEWPORT, RHODE ISLAND

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ELECTROMAGNETIC RADIATION IN SEA WATER

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Aug[redacted] [redacted]60

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(First Revision)

FOREWORD TO FIRST REVISION

This publication supersedes USNUOS Consecutive No. 316, dated April 1960, which should be destroyed in accordance with regulations governing disposal of classified material. The overall intent and conclusions of the original report remain unchanged.

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ABSTRACT

A knowledge of the effects of sea water on electromagnetic waves is essential to any study of torpedo command guidance systems using either radio or wire links. This report presents a set of theoretical curves to illustrate the transmission of electromagnetic waves in a sea water medium. The curves presented are for sea water at 17°C. They are intended as a theoretical starting point for further discussion or investigation.

Curves considered to be most descriptive and useful, and included in this report, are: (1) intrinsic impedance of sea water medium versus frequency; (2) wave length of electromagnetic radiation in sea water; (3) attenuation versus frequency; (4) variation of transmission coefficient with angle of incidence - for both vertical and horizontal polarization of the incident wave; and (5) attenuation to be expected when loss through the interface and through sea water are accounted for.

Conclusions that may be drawn from this survey are: (1) that there are probably no "holes" or "windows" in the electromagnetic spectrum of sea water below 100 kilo-megacycles which may be used for communication with or direct surveillance of submerged vehicles; (2) that radio control or communications systems to be developed should employ, wherever possible, vertically polarized transmitting antennae to maximize the signal passed through the air-sea interface and minimize the dependence of this signal on angle of incidence; and (3) that in the selection of a carrier frequency for proposed underwater vehicle control systems the minimum interface-sea water attenuation formula derived in this report be considered.

In general, this report confirms, in respect to electromagnetic waves, a conclusion drawn by acousticians regarding sound waves; namely, that sea water is a very difficult medium to use for the transmission of signals.

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ACKNOWLEDGMENT

The work accomplished by Mr. T. A. Galib, Head of the Feasibility Branch, Applied Science Department in the solution of equation 22 is gratefully acknowledged. The NAV UNDERWATER ORDSTA IBM 650 computer was programmed to establish its own first approximation and proceed to the single real value of N available from each of the 255 equations required. The prompt completion of this task made the calculation of the transmission coefficients possible.

INTRODUCTION

In the study of torpedo command guidance systems using either radio or wire links, a knowledge of the effects that sea water has on electromagnetic waves is essential.

This report presents a set of theoretical curves describing the transmission of electromagnetic waves in a sea water medium. While there are many references which give information on how to calculate the parameters of interest, these calculations have apparently not been carried out to the point where curves could be drawn to show how index of refraction, index of absorption, attenuation, wave length, and intrinsic impedance vary with frequencies from 100 cps to 100 kmcs. Two partial exceptions to this statement exist in references 1 and 2. The first gives curves of refraction coefficient of sea water from 10 kilocycles to 10 megacycles and a curve of attenuation versus depth for frequencies from 10 to 500 kilocycles. The second gives a theoretical curve showing variation of attenuation of electromagnetic radiation in sea water over the range from 1 megacycle to 100 kilo-megacycles.

Two other sets of curves are required for an understanding of radio transmission through the air-water interface. These are transmission coefficient versus angle of incidence for various frequencies for both horizontal and vertical polarization of the incident wave. These curves have been calculated and plotted.

The curves presented here are for sea water at 17°C. No attempt has been made to determine how far the values for other temperatures will depart from those plotted. These curves are intended to serve as a handy guide to electromagnetic radiation into and through sea water, and as a theoretical starting point for further discussion or investigation.

UNITS AND SYMBOLS

The symbols used throughout are the same as those used in the principal reference (3. "Dielectrics and Waves" by A. Von Hippel). All quantities are expressed in the rationalized m.k.s. system. The subscript 0 designates the quantity in a vacuum, subscript 1 the quantity in air, and subscript 2 the quantity in sea water.

Attenuation constant	$\alpha = \frac{1}{x} \ln \frac{E_o}{E}$	nepers
Complex dielectric constant	$\epsilon = \epsilon' - j\epsilon''$	farad m
Complex index of refraction	$n = n(1 - jk)$	
Complex permeability	$\mu = \mu' - j\mu''$	henry/m
Complex propagation function	$\gamma = \alpha + j\beta$	1/m
Dielectric conductivity	$\sigma = \omega\epsilon''$	mho/m
Dielectric constant (permittivity)	ϵ'	farad/m
Electric field strength	E	volt/m
Electric loss factor	ϵ''	farad/m
Impedance (intrinsic)	Z = E/H	ohm
Index of absorption	$k = \alpha/\beta$	
Index of refraction	$n = \lambda_o/\lambda$	
Magnetic field strength	H	amp/m
Magnetic loss factor	μ''	henry/m
Magnetic permeability	μ'	henry/m
Phase constant	$\beta = 2\pi/\lambda$	1/m

Relative dielectric constant	$\kappa' = \epsilon'/\epsilon_o$	
Relative magnetic permeability	$\kappa'_m = \mu'/\mu_o$	
Wave length	λ	meters
	$\omega = 2\pi f$	rad/sec
	$\epsilon_o = \frac{1}{36\pi} \times 10^{-9}$	farad/m
	$\mu_o = 4\pi \times 10^{-7}$	henry/m
	$Z_o = \sqrt{\frac{\mu_o}{\epsilon_o}} = 376.6$	ohms

THEORY

Fundamental to all of the following calculations are the values of the intrinsic impedance of sea water, Z_2, for the frequencies from 100 cycles per second to 100 kilo-megacycles per second. Reference 4 gives experimental values for the real and imaginary parts of κ_2^* , the relative dielectric constant of sea water at 17°C. This graph is reproduced as figure 1. The symbols on the curves have been modified to agree with the preceding section (Units and Symbols).

$$Z_2 = \sqrt{\frac{\mu_2^*}{\epsilon_2^*}} = \sqrt{\frac{\mu_2' - j\mu_2''}{\epsilon_2' - j\epsilon_2''}} \qquad (1)$$

Since there are assumed to be no magnetic losses in the sea water,

$$\mu_2'' = 0 \quad \text{and} \quad Z_2 = \sqrt{\frac{\mu_2'}{\epsilon_2' - j\epsilon_2''}} \qquad (2)$$

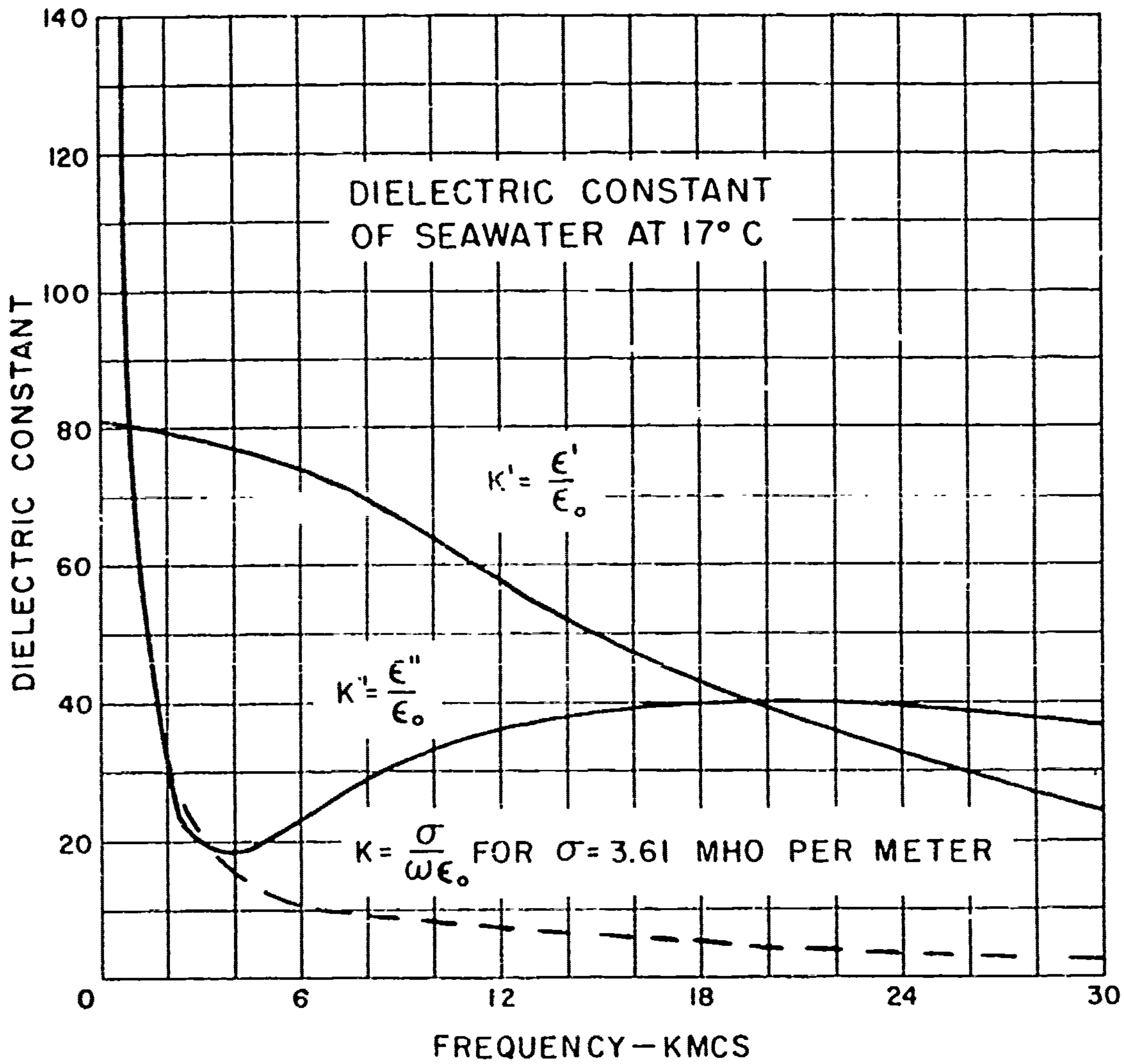

DIELECTRIC CONSTANT OF SEAWATER AT 17° C
DIELECTRIC CONSTANT
FREQUENCY—KMCS
140
120
100
80
60
40
20
0
6
12
18
24
30
$K' = \frac{\epsilon'}{\epsilon_o}$
$K'' = \frac{\epsilon''}{\epsilon_o}$
$K = \frac{\sigma}{\omega \epsilon_o}$ FOR $\sigma = 3.61$ MHO PER METER

FIGURE 1

Figure 1 shows that up to 2 kmc, $\epsilon''_2 = \sigma/\omega$. Therefore, from 100 cps to 2 kmc, Z_2 was calculated using these values of ϵ'' , with σ = 3.61 mho-meter and assuming that $\epsilon' = 81\epsilon_o$. Above 2 kmc to 30 kmc, the values for K'_2 and K''_2 were taken from the graph to be applied as follows:

$$Z_2 = \sqrt{\frac{K'_{m2}\ \mu_o}{K'_2\epsilon_o - jK''_2\epsilon_o}} \tag{3}$$

Since $K'_{m2} = 1$, (4)

$$Z_2 = \sqrt{\frac{\mu_o}{K'_2\epsilon_o - j\,K''_2\epsilon_o}}$$

The complex index of refraction is found in terms of the intrinsic impedances of air and sea water. Numbers in brackets [ ] refer to equation numbers in reference 3.

By [7.25], $Z = j\omega\mu^* / \gamma$; (5)

and by [20.9], $\dfrac{\gamma_2}{\gamma_1} = n^*_{21}\,(1 - jk_2)$ (6)

Then $n^*_{21}\,(1 - jk_2) = \dfrac{\gamma_2}{\gamma_1} = \dfrac{j\omega\mu^*_2/Z_2}{j\omega\mu^*_1/Z_1}$ (7)

Since it is assumed tnat

$$\mu^*_2 = \mu^*_1\ ,\ n^*_{21}(1 - jk_2) = \frac{Z_1}{Z_2}\ ; \tag{8}$$

where, according to [20.3],

$$n_{21} = \beta_2 / \beta_1 \tag{9}$$

$$k_2 = \alpha_2 / \beta_2 \tag{10}$$

The computation can now proceed, using equation (8) to determine index of refraction n_{21} and absorption coefficient k_2 from the values calculated for Z_2 and the value $Z_1 = Z_0$.

Since $\beta_1 = 2\pi/\lambda_1$, β_2 may be found from equation (9), While α_2, the attenuation constant, may now be found from equation (10). The values of λ_2, the wave length in sea water, may be calculated from the relationship $\beta_2 = 2\pi/\lambda_2$; or, more directly,

$$n_{21} = \frac{\beta_2}{\beta_1} = \frac{2\pi/\lambda_2}{2\pi/\lambda_1} = \frac{\lambda_1}{\lambda_2} \tag{11}$$

The transmission coefficient is the ratio of field strength just below the air-sea water interface to field strength just above the interface. [15.16] in reference 3 gives the two equations necessary. For the E vector normal to the plane of incidence as shown in figure 2, and defined here as a horizontally polarized wave:

$$t_{en} = \left(\frac{E_t}{E_i}\right)_n = \frac{2Z_2 \cos\phi}{Z_2 \cos\phi + Z_1 \cos\psi} \tag{12}$$

For the E vector parallel to the plane of incidence as shown in figure 3, and defined here as a vertically polarized wave:

$$t_{ep} = \left(\frac{E_t}{E_i}\right)_p = \frac{2Z_2 \cos\phi}{Z_2 \cos\psi + Z_1 \cos\phi} \tag{13}$$

In these expressions ϕ is the angle of incidence, ψ is the angle of refraction, and Z_1 and Z_2 are the intrinsic impedances of air and sea water respectively.

Snell's Law gives the relationship between ϕ and ψ as:

$$\sin\phi = \frac{\gamma_2}{\gamma_1} \sin\psi \tag{14}$$

However, in the case of lossy dielectrics, such as sea water, the ratio γ_2/γ_1 is complex and equation (14) cannot be used. In reference 3, Von Hippel develops a way around this mathematical impasse based on a geometrical index of refraction N for the planes of constant phase, which "can be measured by the customary optical methods as long as medium 2 (sea water) is of sufficient transparency." This index of refraction is a function of the angle of incidence. Four equations are shown, [20.10] and [20.11]. These equations define the relationships between β_1, β_2, α_2, N, ψ' the geometric angle of refraction, and two quantities, p and q, introduced to account for the shift in ψ to ψ'. These equations are:

$$\frac{\sin\phi}{\sin\psi'} = N = \frac{\sqrt{q^2+\beta_1^2\sin^2\phi}}{\beta_1} \qquad (15)$$

$$\beta_1^2 N - p^2 = \beta_2^2 - \alpha_2^2 \qquad (16)$$

$$pq = \alpha_2 \beta_2 \qquad (17)$$

$$\beta_1 N p = \frac{\alpha_2 \beta_2}{\cos\psi'} \qquad (18)$$

Since $\alpha_2 = k_2 \beta_2$, and $\beta_2 = n_{21} \beta_1$, equation (17) can be rewritten as:

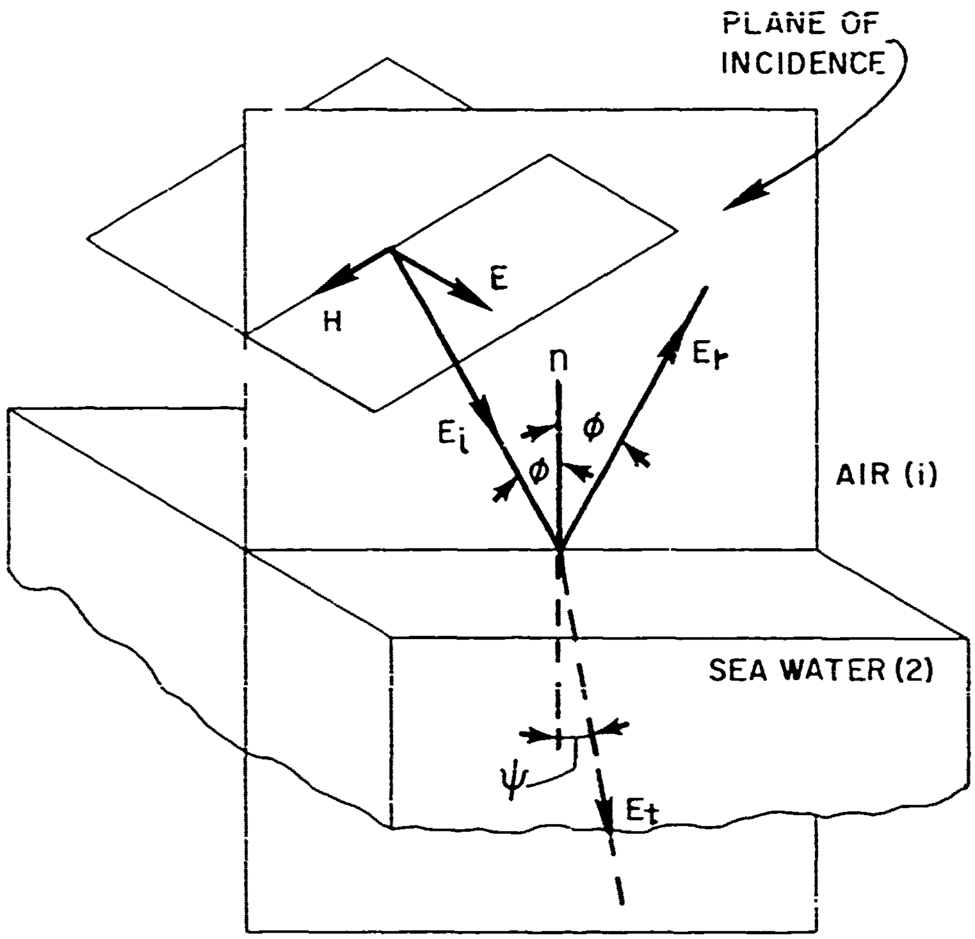
$$p = \frac{(k_2 \beta_2)(n_{21}\beta_1)}{q} \qquad (19)$$

Combining (19) with (16) gives:

$$\beta_1^2 \left(N - \frac{n_{21}^2 k_2^2 \beta_2^2}{q^2}\right) = \beta_2^2 (1-k_2^2) \quad ;$$

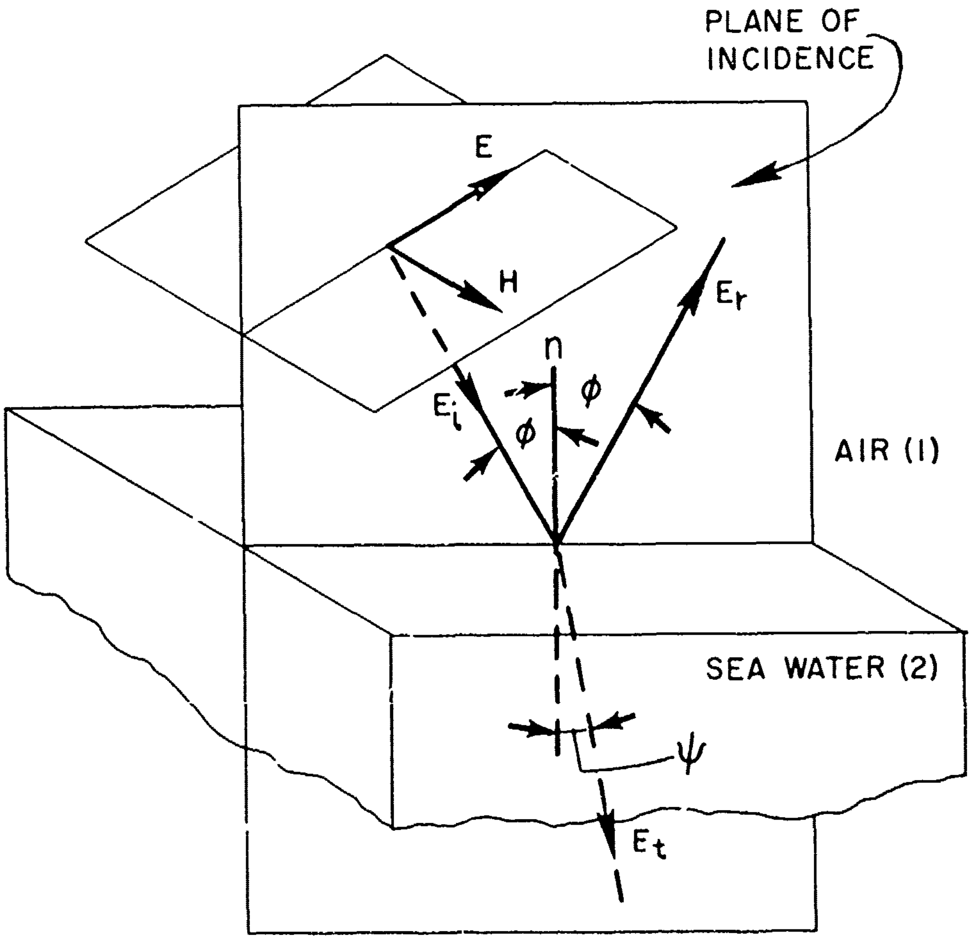
$$\frac{n_{21}^2 k_2^2 \beta_2^2}{q^2} = N - n_{21}^2 (1-k_2^2) \quad ;$$

$$q^2 = \frac{n_{21}^2 k_2^2 \beta_2^2}{N - n_{21}^2(1-k_2^2)} \qquad (20)$$



REFLECTION AND REFRACTION FOR A HORIZONTALLY POLARIZED E M WAVE

FIGURE 2



REFLECTION AND REFRACTION FOR A VERTICALLY POLARIZED E M WAVE

FIGURE 3

Solving (15) for q^2,

$$q^2 = \beta_1^2 \, (N^2 - \sin^2 \phi) \tag{21}$$

Equating (20) and (21),

$$N^2 - \sin^2 \phi = \frac{\beta_2^2}{\beta_1^2} \; \frac{n_{21}^2 \; k_2^2}{N - n_{21}^2 \; (1 - k_2^2)} \; ;$$

$$N^3 - N^2 \left[n_{21}^2 (1 - k_2^2) \right] - N \left[\sin^2 \phi \right] + (\sin^2 \phi) \left[n_{21}^2 (1 - k_2^2) \right] - n_{21}^4 \; k_2^2 = 0 \tag{22}$$

This equation expresses the geometric index of refraction in terms of the calculated quantities n_{21} and k_2 and values of ϕ between 0° and 90°. There will be at least one positive real root for all values of n_{21}, k_2 and ϕ for the frequencies considered in this study.

For frequencies up to 10 Mc, $k_2 = 1$; and equation (22) reduces to $N^3 - N \; [\sin^2 \phi] - n_{21}^4 = 0$. (23)

The solution of equation (23) by the algebraic method given in reference 5 indicates that the coefficient of N can be neglected.

Therefore: $N = (n_{21})^{4/3}$ (24)
for frequencies up to and including 10 Mc. However, for this study, these equations were solved by a computer for all values of n_{21}, k2, and $\sin \phi$.

Values of ψ' are now obtained from a modified version of Snell's Law:

$$\sin \psi' = \frac{\sin \phi}{N} \; . \tag{25}$$

The resulting pairs of values of ϕ and ψ' are inserted in equations (12) and (13), with the frequency dependent values of Z_2, to calculate the transmission coefficients.

CURVES

Of the many curves which may be plotted from the results of the calculations made, the following are considered to be the most descriptive and useful.

1. Intrinsic impedance of the sea water medium versus frequency is shown in curve 1 (figure 4). While the plot of phase angle is somewhat distorted by the log-log scales, it is felt that this distortion is permissible in order to keep the amplitude and phase angle together on one graph. The plot shows that the impedance varies directly as the square root of frequency up to 100 Mc. with the phase angle at 45 degrees. The dip in the phase angle curve corresponds with the minimum in κ_2'' at approximately 3.5 kmcs.

2. Curve 2 (figure 5) is a plot of wave length of electromagnetic radiation in sea water. λ_2 varies inversely as the square root of frequency up to 100 Mc.

3. Curve 3 (figure 6) shows that the attenuation varies directly as the square root of the frequency up to 100 Mc. Of at least passing interest is the notch in the region between 3.5 and 4 kilo-megacycles. The depth of the notch, measured from the local maximum at about 2 kmc, is at most 5 nepers per meter. (In db, this is 5 x 8.686 = 43.4 db.) Since the level in this region is about 70 nepers per meter (608 db per meter), the percentage decrease is a minute 0.8 per cent. Beyond this valley, the curve rises sharply to the imposing height at 100 kmcs of 4000 nepers per meter or 34,800 db per meter.

4. Curve 4 (figure 7) shows the variation of transmission coefficient with angle of incidence for vertical polarization of the incident wave. For the lower frequencies shown, the transmission coefficient is practically independent of angle of incidence for angles below 89.5°. The angles of refraction were always less than 6.5° for the values of ϕ chosen. For 10 kmc and below, the angles of refraction were always below 1°. Curves 5 and 6 (figures 8 and 9) show transmission coefficient and the phase angle between the incident and refracted waves, plotted on an expanded scale of angle of incidence between 80 and 90 degrees.

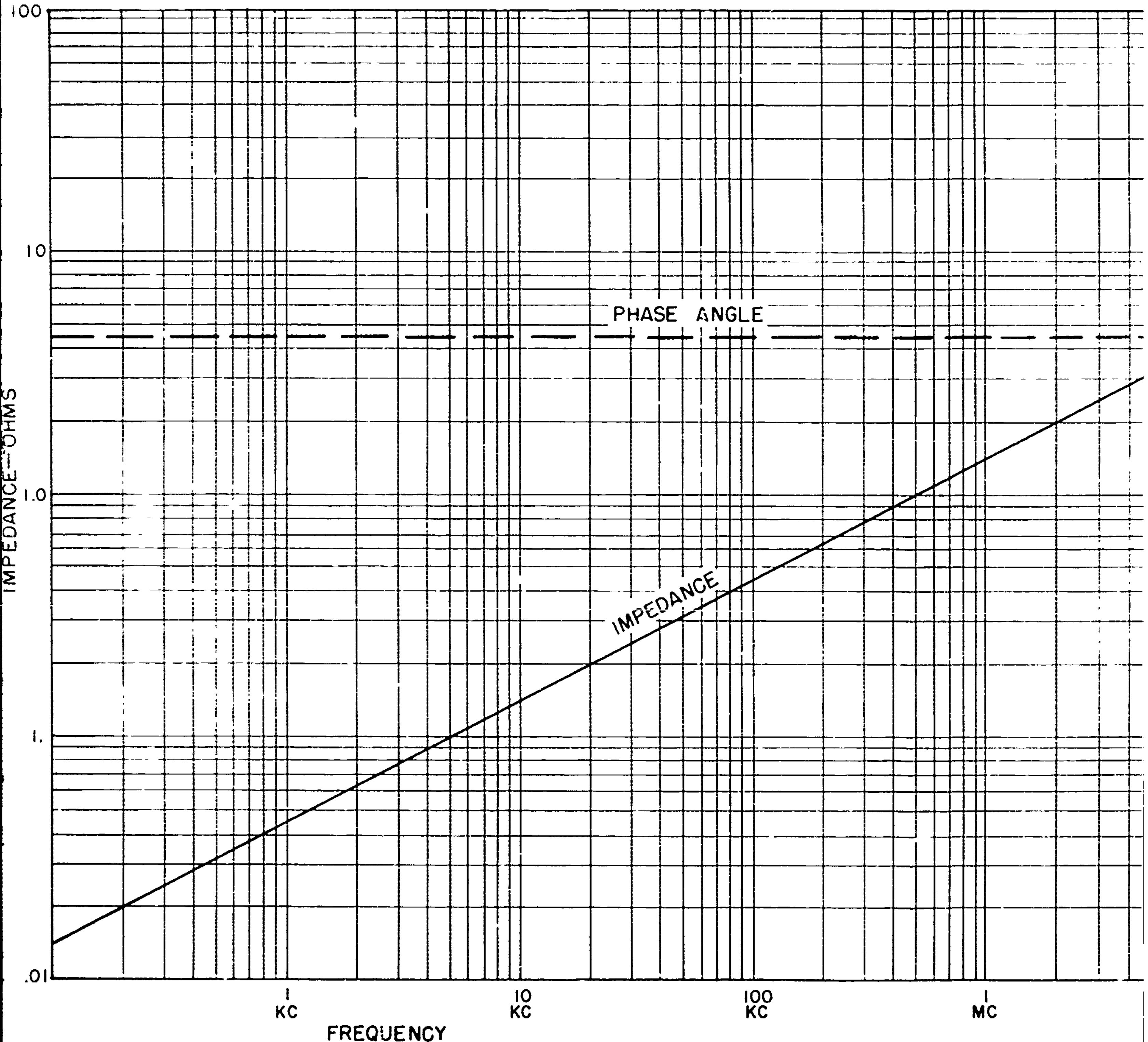
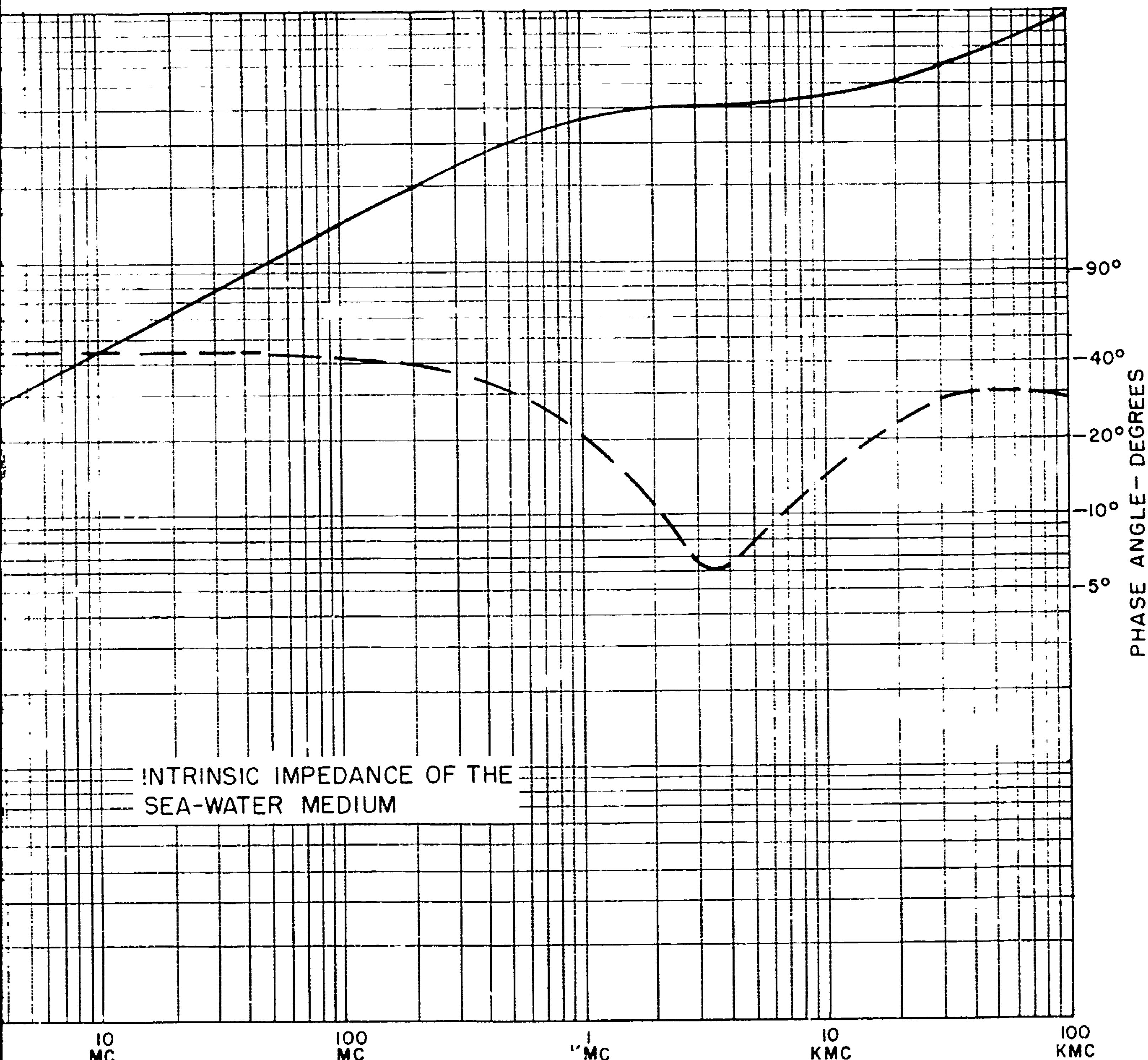

100
10
1.0
1.
.01
IMPEDANCE—OHMS
PHASE ANGLE
IMPEDANCE
1
KC
10
KC
100
KC
1
MC
FREQUENCY

FIGURE 4


INTRINSIC IMPEDANCE OF THE SEA-WATER MEDIUM
90°
40°
20°
10°
5°
PHASE ANGLE - DEGREES
10 MC
100 MC
1 KMC
10 KMC
100 KMC

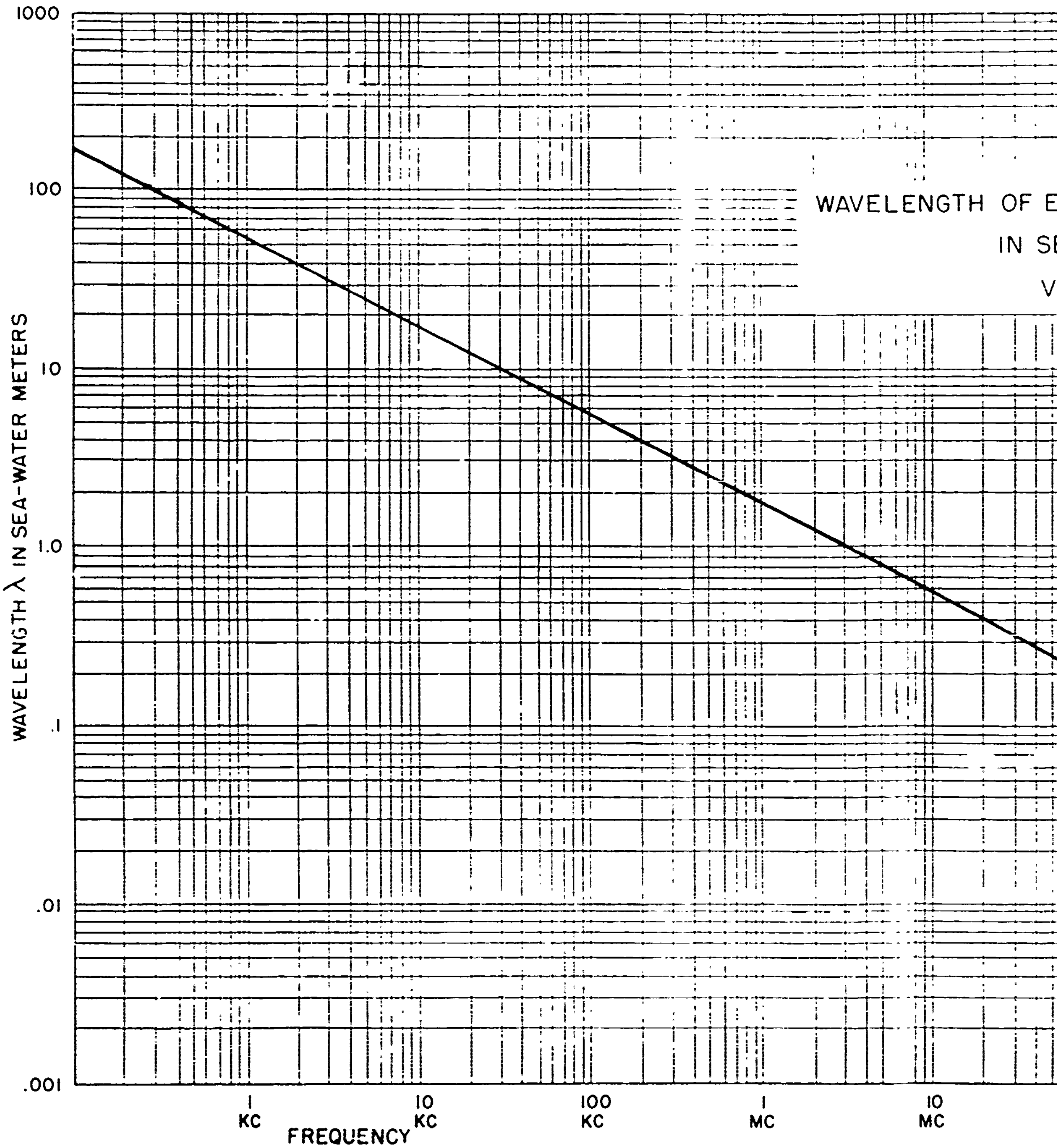
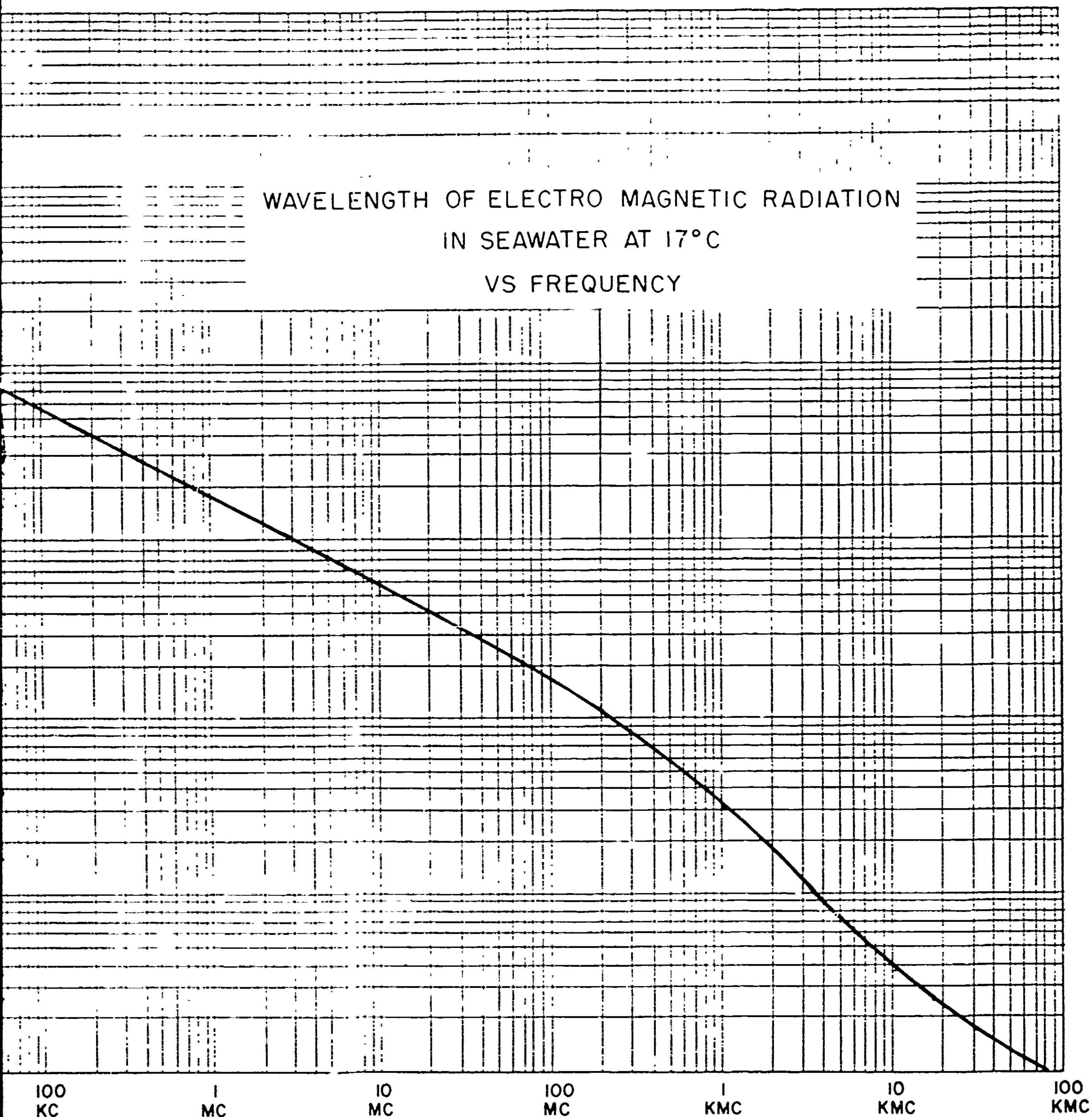

WAVELENGTH OF E
IN SE
V
WAVELENGTH λ IN SEA-WATER METERS
1000
100
10
1.0
.1
.01
.001
1 KC
10 KC
100 KC
1 MC
10 MC
FREQUENCY

FIGURE 5


WAVELENGTH OF ELECTRO MAGNETIC RADIATION
IN SEAWATER AT 17°C
VS FREQUENCY
100 KC
1 MC
10 MC
100 MC
1 KMC
10 KMC
100 KMC

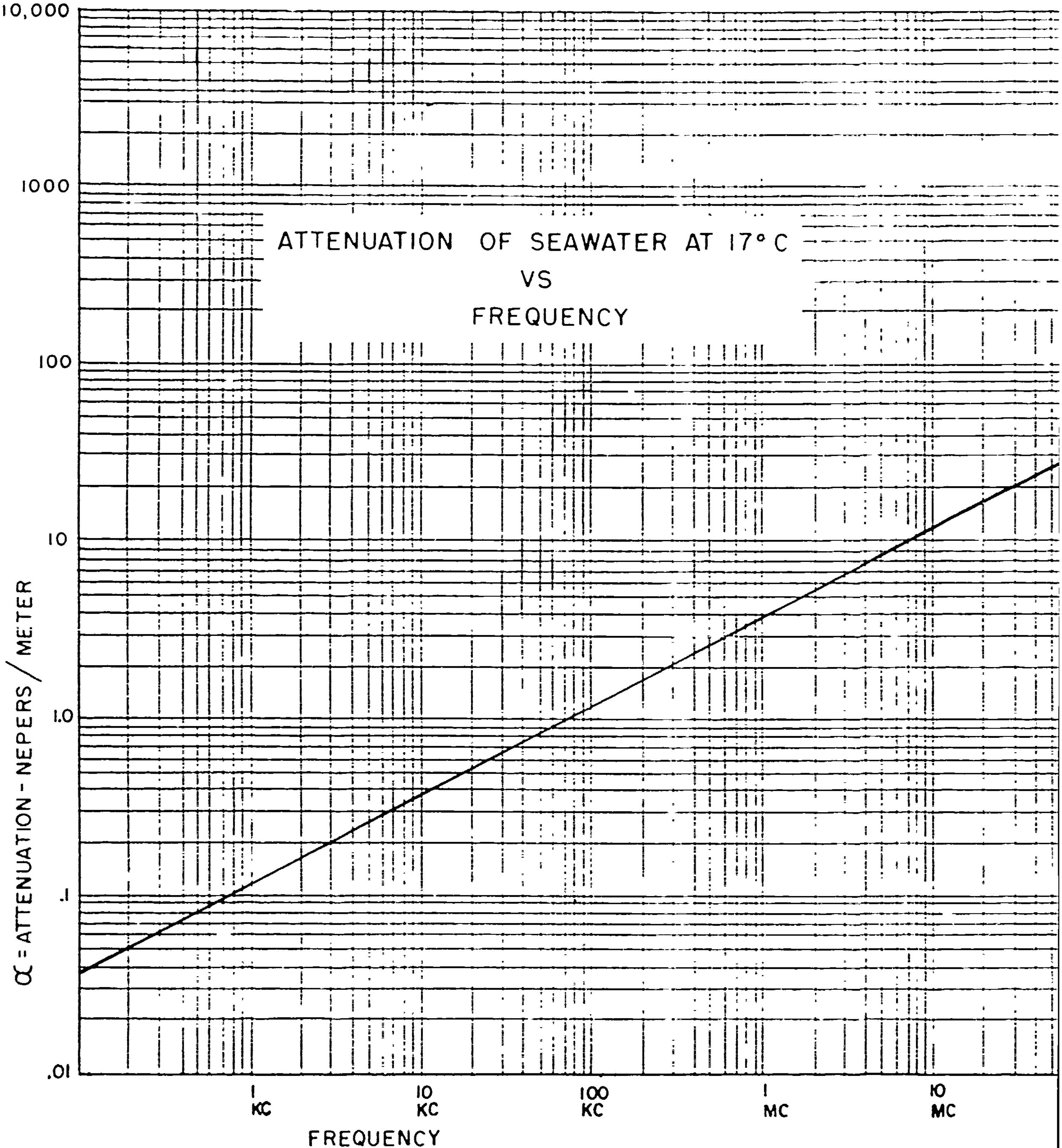
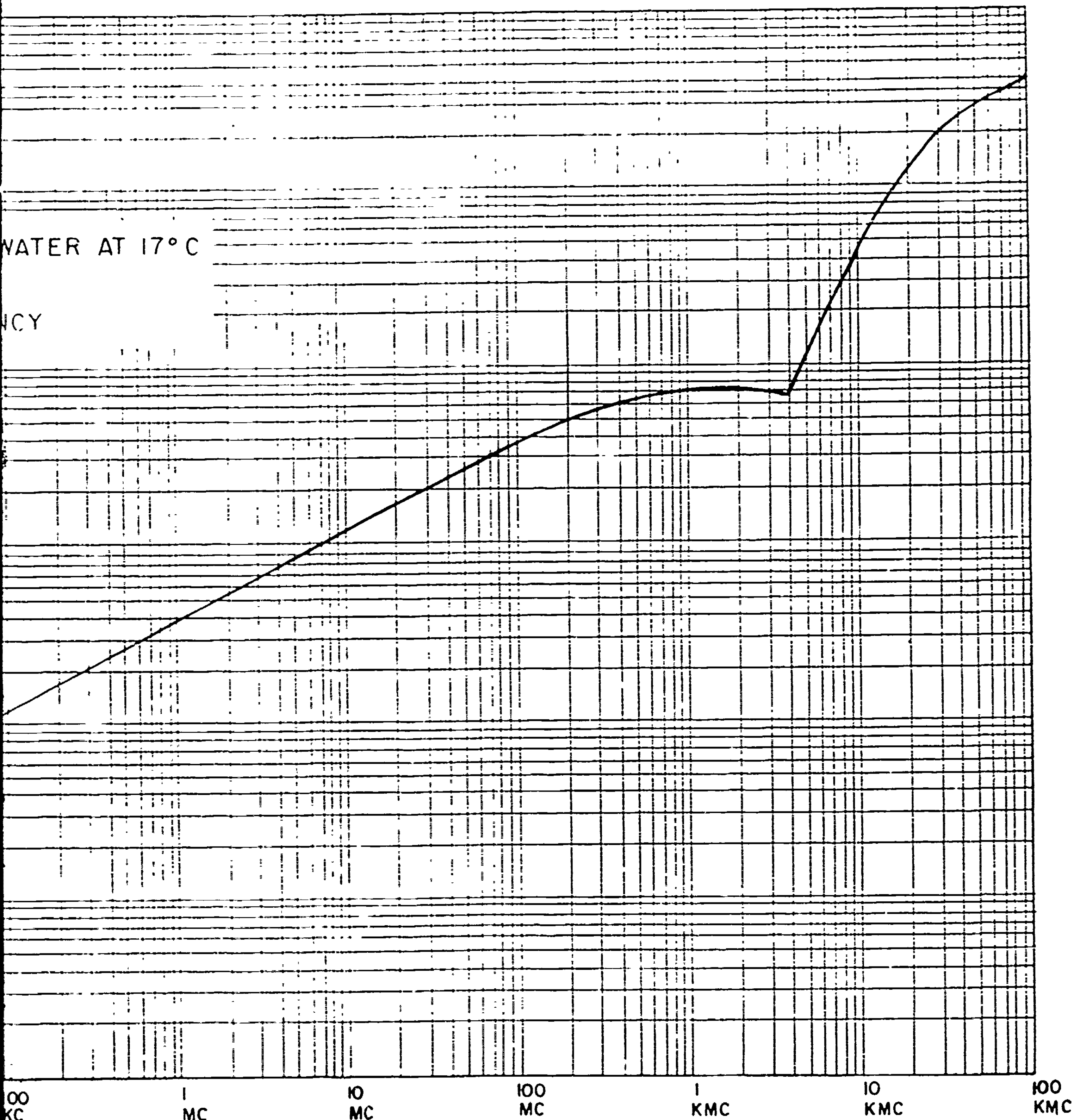

ATTENUATION OF SEAWATER AT 17° C
VS
FREQUENCY
10,000
1000
100
10
1.0
.1
.01
α = ATTENUATION - NEPERS / METER
1 KC
10 KC
100 KC
1 MC
10 MC
FREQUENCY

FIGURE 6


WATER AT 17° C
NCY
100 KC
1 MC
10 MC
100 MC
1 KMC
10 KMC
100 KMC

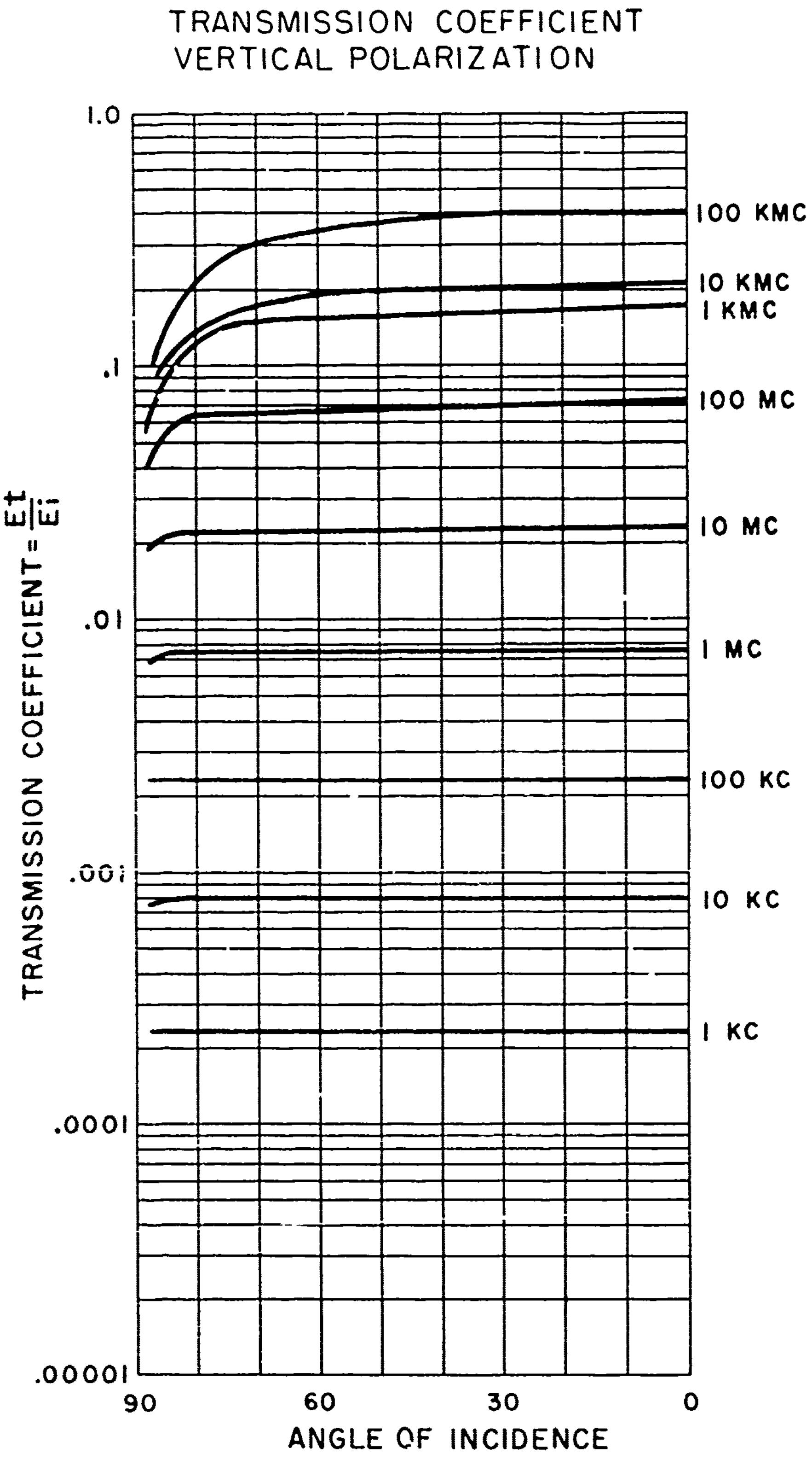

TRANSMISSION COEFFICIENT
VERTICAL POLARIZATION
1.0
.1
.01
.001
.0001
.00001
100 KMC
10 KMC
1 KMC
100 MC
10 MC
1 MC
100 KC
10 KC
1 KC
TRANSMISSION COEFFICIENT = Et/Ei
90
60
30
0
ANGLE OF INCIDENCE

FIGURE 7

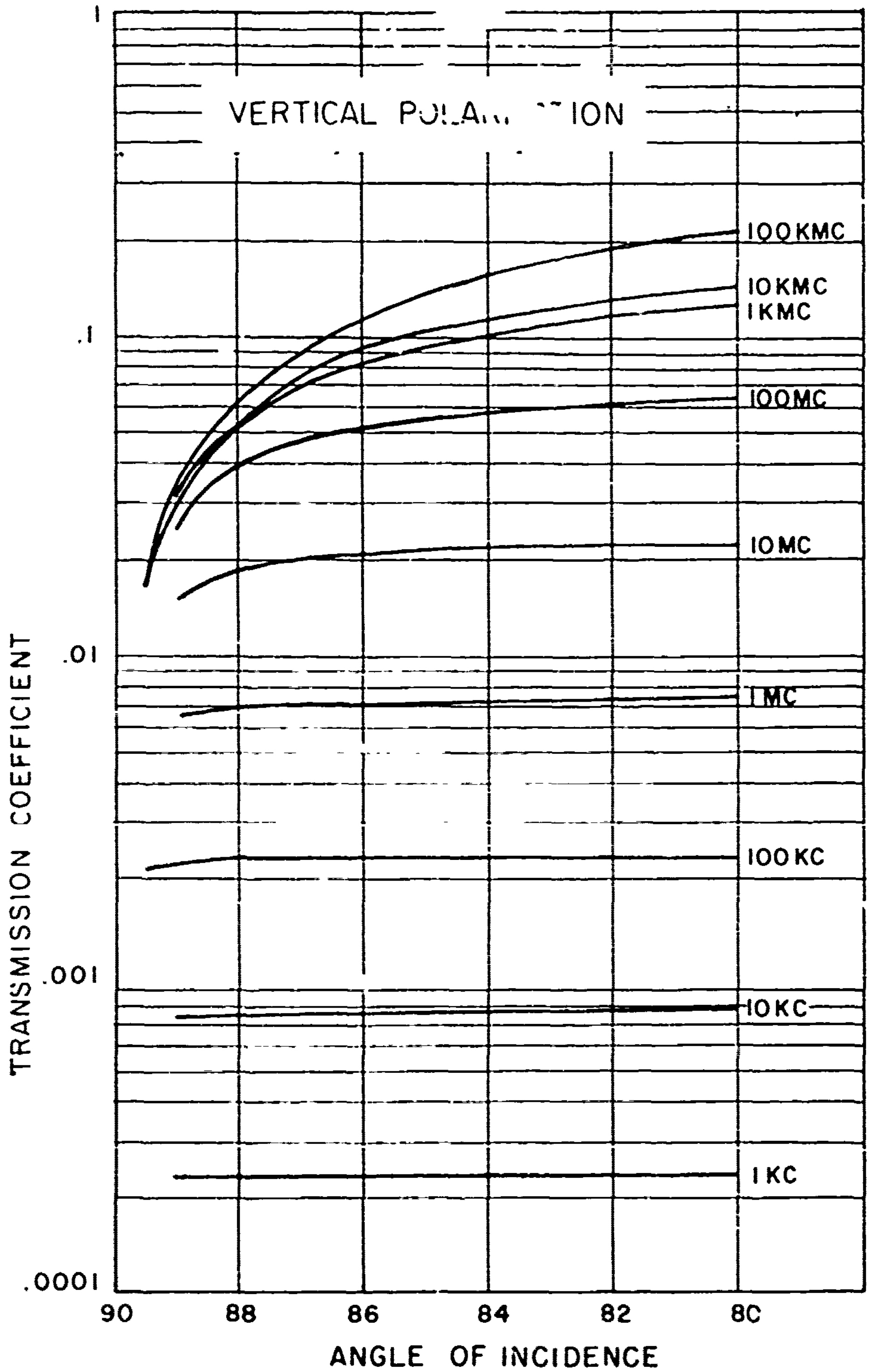

VERTICAL POLA... ION
100 KMC
10 KMC
1 KMC
100 MC
10 MC
1 MC
100 KC
10 KC
1 KC
1
.1
.01
.001
.0001
TRANSMISSION COEFFICIENT
90
88
86
84
82
80
ANGLE OF INCIDENCE

FIGURE 8

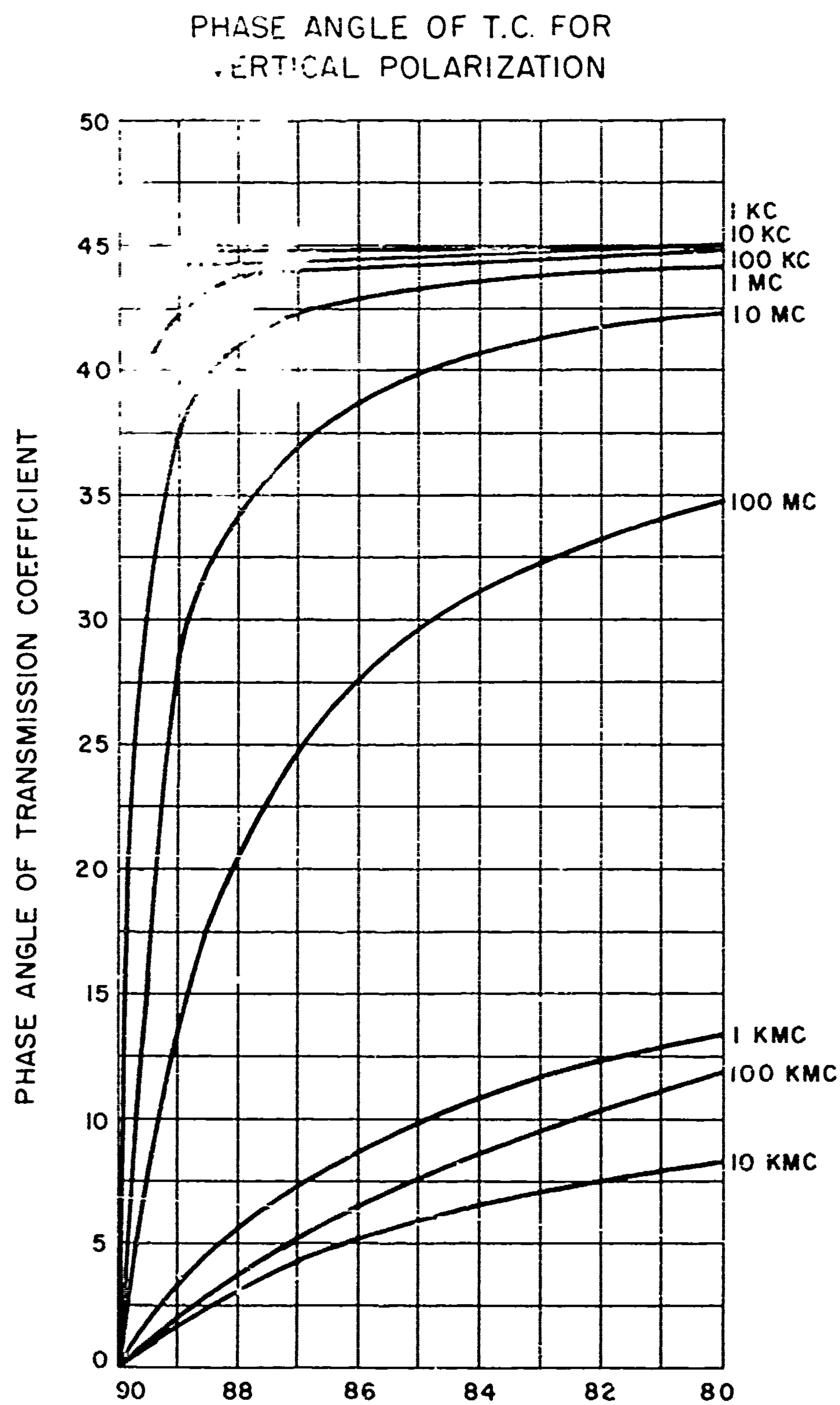

PHASE ANGLE OF T.C. FOR
VERTICAL POLARIZATION
PHASE ANGLE OF TRANSMISSION COEFFICIENT
50
45
40
35
30
25
20
15
10
5
0
90
88
86
84
82
80
1 KC
10 KC
100 KC
1 MC
10 MC
100 MC
1 KMC
100 KMC
10 KMC

FIGURE 9

5. Curves 7, 8 and 9 (figures 10, 11 and 12) repeat those of the preceding paragraph for horizontal polarization of the incident wave. In this case, the transmission coefficient falls rather rapidly toward zero as the angle of incidence increases. It should be noted that the points at zero angle of incidence, at corresponding frequencies, are identical for both horizontal and vertical polarization. For a wave directed perpendicular to an interface, the sense of polarization is lost.

It is noted that as frequency increases the transmission coefficient increases, as does also the attenuation within the sea water medium. In the region of the frequency spectrum, where we may expect to obtain 10 to 50 per cent of the incident field strength on the under side of the interface, the attenuation is so high that the signals are useless. In the region where attenuation becomes more nearly reasonable, the losses through the interface become large.

6. Curve 10 (figure 13) shows the total attenuation to be expected when loss through the interface and loss through sea water to any selected depth are accounted for. Vertical polarization of the incident signal was chosen because the transmission coefficient is virtually independent of angle of incidence. In addition the curves obtained will represent the most favorable limit for total attenuation. Horizontally polarized signals will give higher values for all angles of incidence.

The following functions were obtained graphically:

$$\alpha \text{ (interface)} = 13.25\ f^{-.0667} \tag{26}$$

$$\alpha \text{ (sea water)} = .0037\ D\sqrt{f}\ ; \tag{27}$$

where f is the frequency in cycles per second, D is the depth of penetration in meters and α is attenuation in nepers. These values of attenuation agree with the results shown in reference 1. The frequency at which the total attenuation is a minimum for any fixed depth D is given by:

$$f = \left[\frac{478}{D}\right]^{1.76} \tag{28}$$

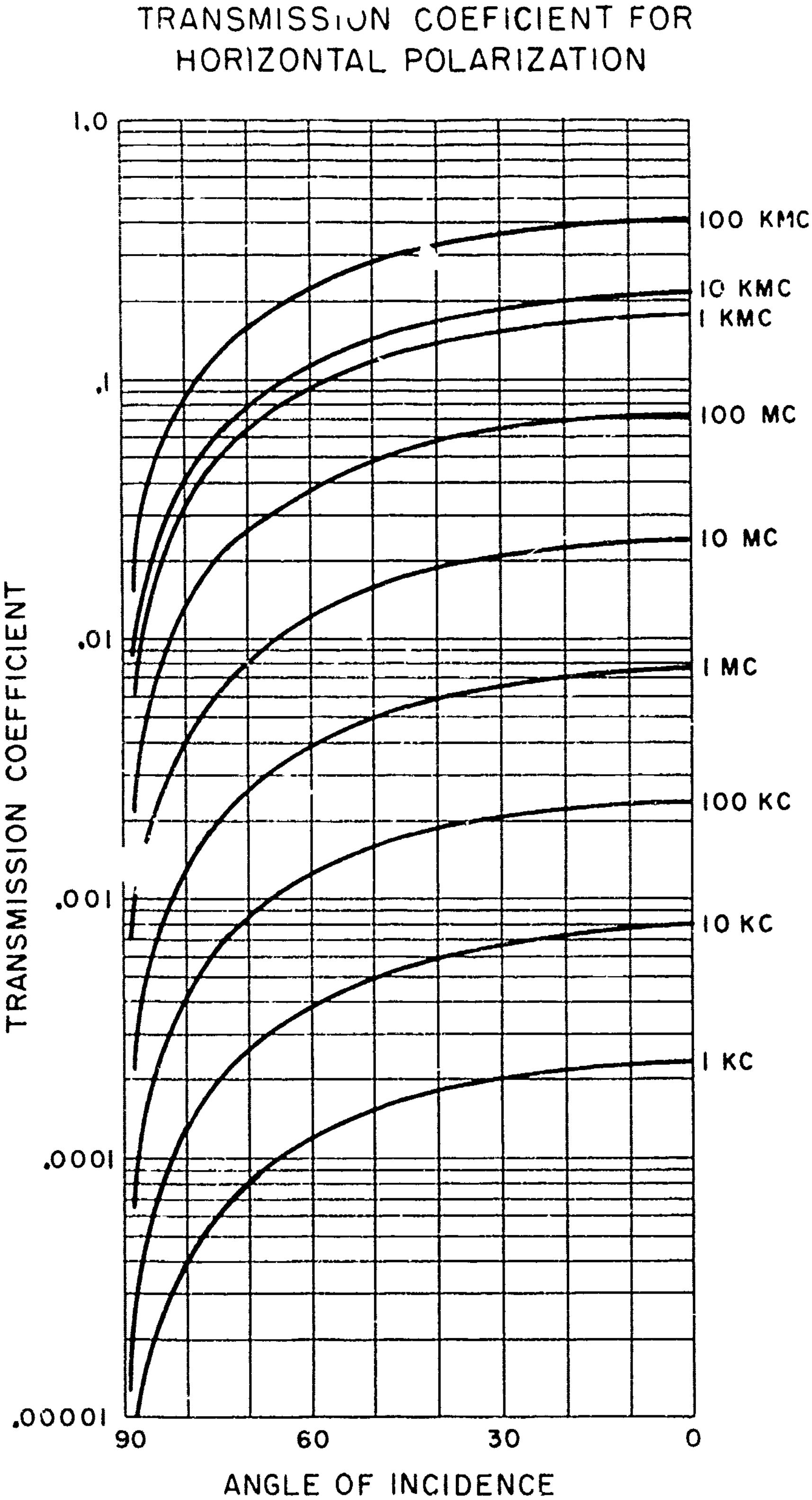

TRANSMISSION COEFICIENT FOR HORIZONTAL POLARIZATION
1.0
.1
.01
.001
.0001
.00001
TRANSMISSION COEFFICIENT
90
60
30
0
ANGLE OF INCIDENCE
100 KMC
10 KMC
1 KMC
100 MC
10 MC
1 MC
100 KC
10 KC
1 KC

FIGURE 10

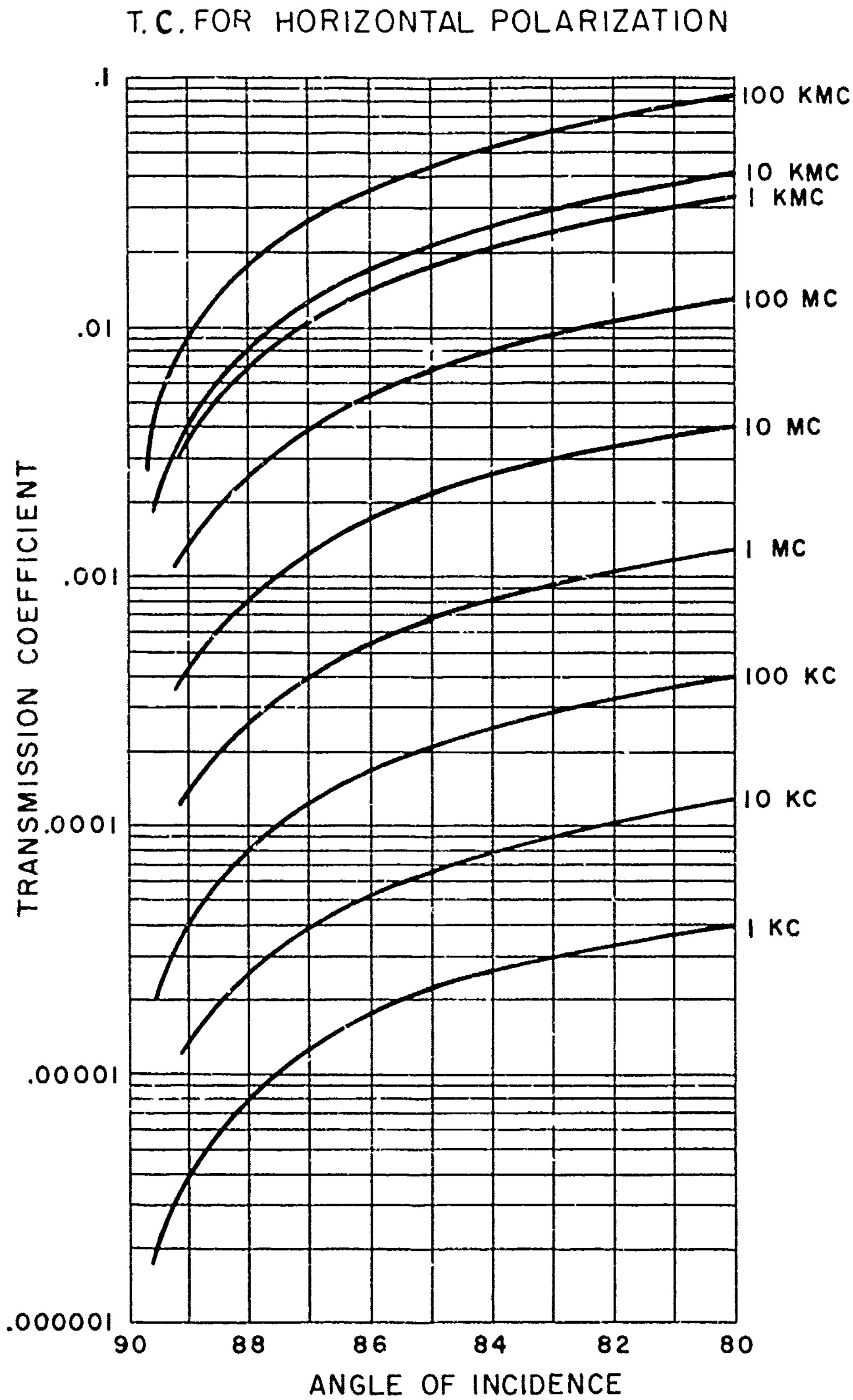

T.C. FOR HORIZONTAL POLARIZATION
TRANSMISSION COEFFICIENT
ANGLE OF INCIDENCE
.1
.01
.001
.0001
.00001
.000001
90
88
86
84
82
80
100 KMC
10 KMC
1 KMC
100 MC
10 MC
1 MC
100 KC
10 KC
1 KC

FIGURE 11

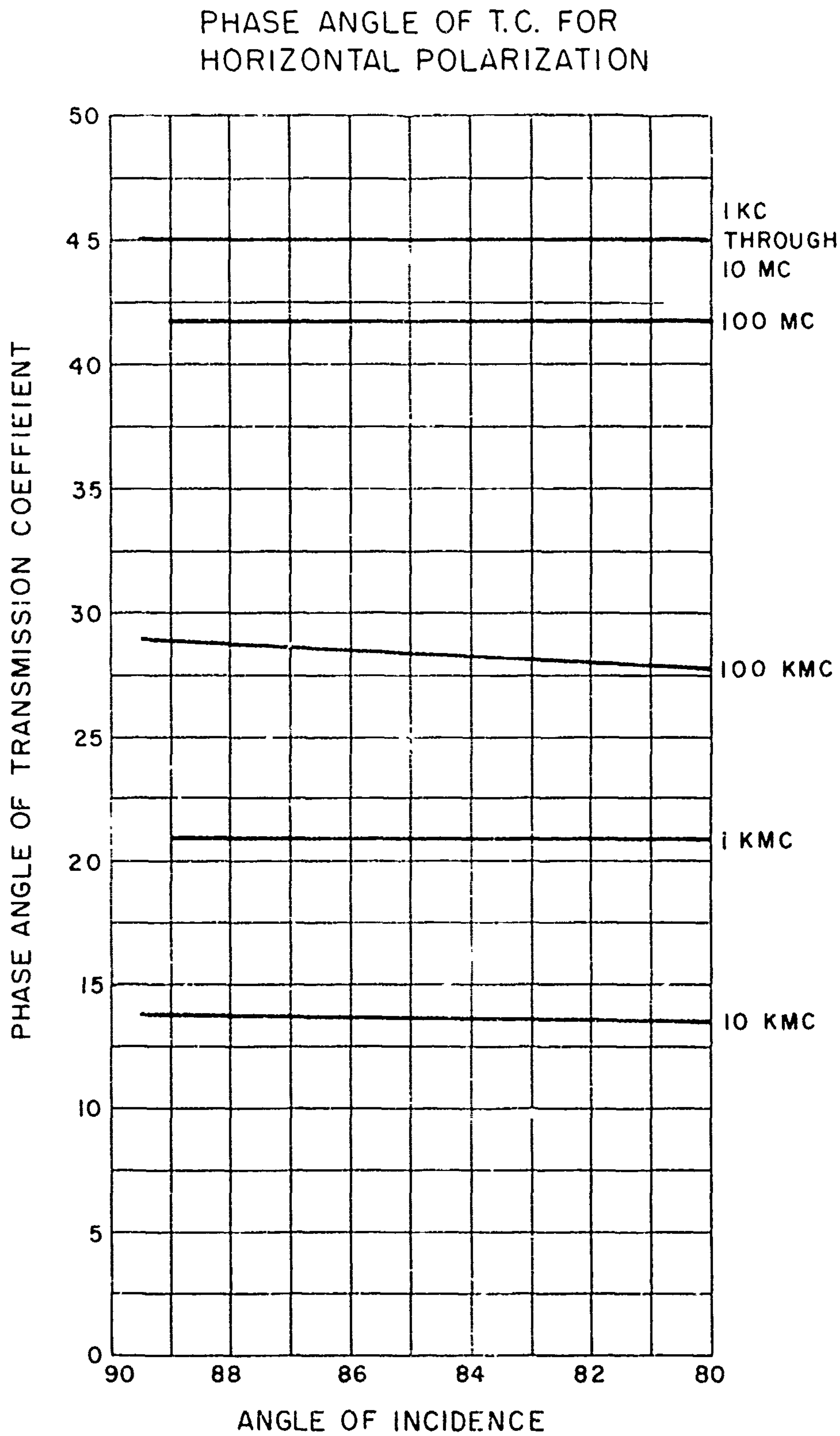
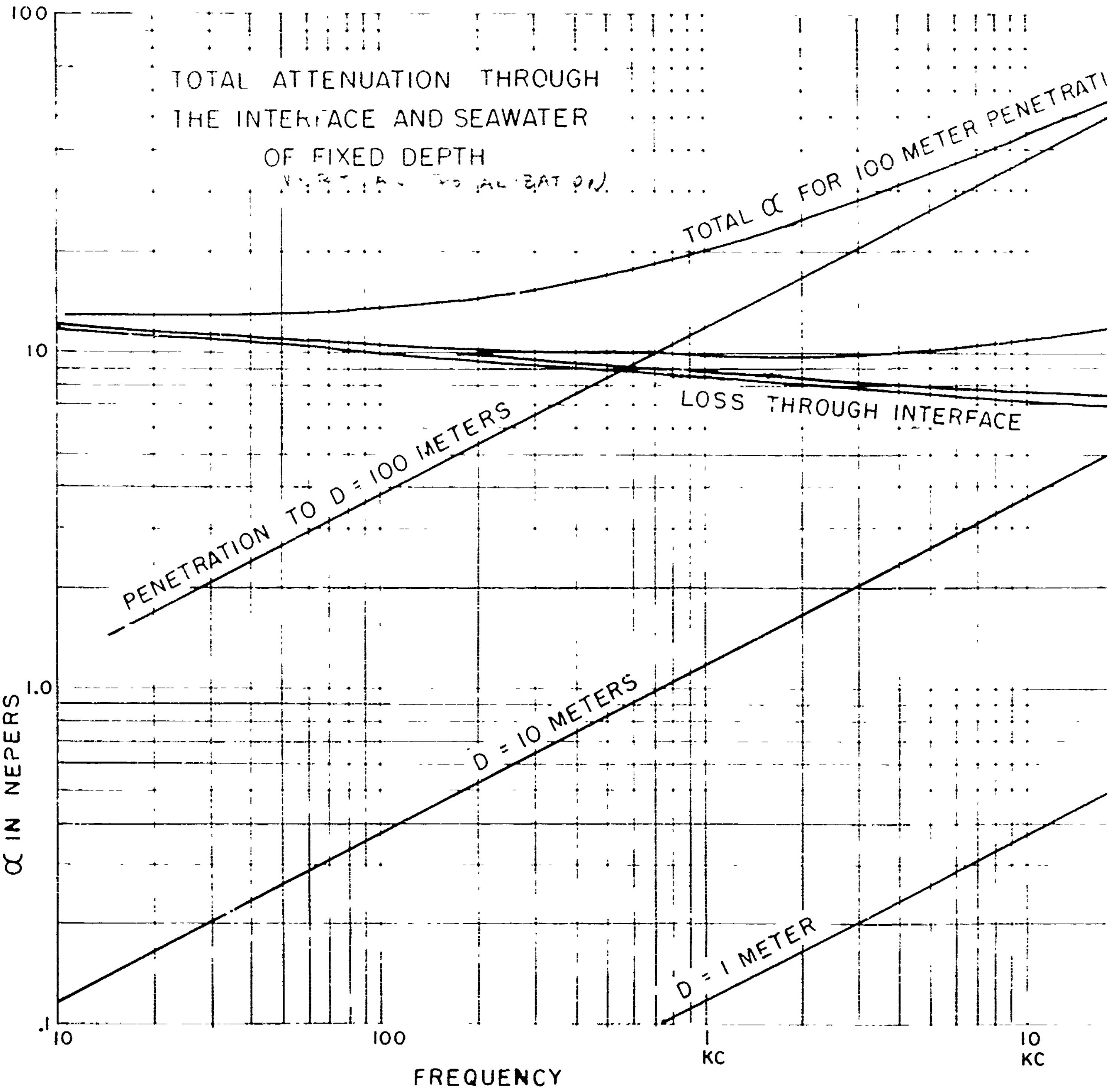

PHASE ANGLE OF T.C. FOR
HORIZONTAL POLARIZATION
PHASE ANGLE OF TRANSMISSION COEFFICIENT
ANGLE OF INCIDENCE
0
5
10
15
20
25
30
35
40
45
50
90
88
86
84
82
80
1 KC
THROUGH
10 MC
100 MC
100 KMC
1 KMC
10 KMC

FIGURE 12



TOTAL ATTENUATION THROUGH
THE INTERFACE AND SEAWATER
OF FIXED DEPTH
TOTAL α FOR 100 METER PENETRATI
LOSS THROUGH INTERFACE
PENETRATION TO D = 100 METERS
D = 10 METERS
D = 1 METER
α IN NEPERS
FREQUENCY
100
10
1.0
.1
10
100
1 KC
10 KC

FIGURE 13

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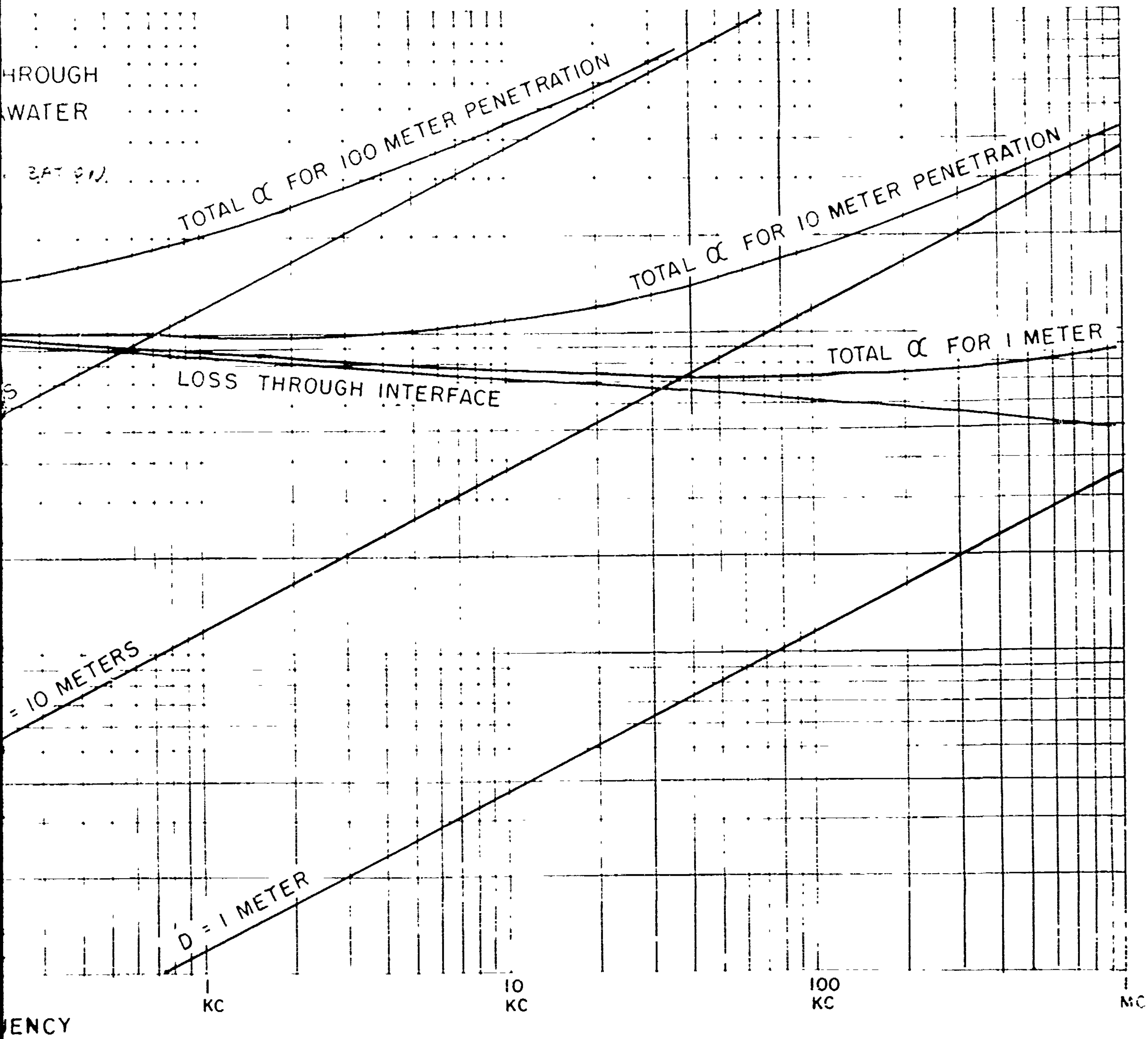

2

The table below gives some representative values. These are rather optimistic minima for total attenuation to the depth selected. Frequencies different from those given will increase the total α , as will the use of horizontal polarization.

D	f for α Min.	α Total at f
100 m.	16 cps	13 nepers (113 db)
10 m.	900 cps	9.8 nepers (85 db)
1 m.	52 kcs	7.2 nepers (62.5 db)

CONCLUSIONS

The conclusions which may be drawn from this brief survey are:

1. That there are probably no "holes" or "windows" in the electromagnetic spectrum of sea water below 100 kilo-megacycles which may be used for communication with or direct surveillance of submerged vehicles.

2. That radio control or communications systems to be developed should employ, wherever possible, vertically polarized transmitting antennae, to maximize the signal passed through the air-sea interface and minimize the dependence of this signal on angle of incidence.

3. That in the selection of a carrier frequency for proposed underwater vehicle control systems, the minimum interface-sea water attenuation formula be considered. This formula, (28) in the body of this report, is

$$f \quad \text{min.} = \left[\frac{478}{D}\right]^{1.76} \qquad ;$$

where D is the required depth of penetration in meters.

In general we may confirm, for the case of electromagnetic waves, a conclusion drawn by acousticians for sound waves; that is, sea water is a very difficult medium to use for the transmission of signals.

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